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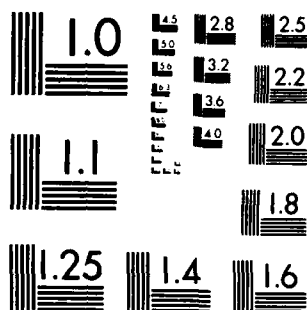   N00014-82-F-0123
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Desirable electron attachment and electron drift characteristics of gases for possible use in diffuse-discharge switches are indicated. Gas mixtures for possible use in externally sustained (e-beam) diffuse-discharge switches are suggested on the basis of electron attachment rate constants and electron drift velocities measured as a function of the density-normalized electric field E/N. Of particular promise are mixtures of Ar and C_3F_8.

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BASIC STUDIES OF GASES FOR FAST SWITCHES

Semiannual Status Report

by

L. G. Christophorou and S. R. Hunter
Health and Safety Research Division

Oak Ridge National Laboratory
P. O. Box X
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April 1983

BASIC STUDIES OF GASES FOR FAST SWITCHES

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I. INTRODUCTION

There has been increasing interest in recent years in the possibility
of using inductive energy storage devices as a means of storing and
transferring energy in numerous repetitive, pulsed-power applications.
The major advantages to be realized using this technology are that the
intrinsic energy density of these devices are of the order of 10^2 to 10^3
times those for capacitive systems[1] and that this energy can be transferred
to the load on the very short-time scale of a few nanoseconds. The
major technological problem to be faced when using this type of energy-
storage system is in the design of a repetitive opening switch. A
leading contender for this switching concept is an externally sustained
diffuse gas discharge operating at gas pressures of one to several
atmospheres. Two possible electron sources have been proposed for the
external control of the discharge current. They are by means of gas
ionization by pulsed electron beams (e-beams)[2] or by resonant ionization
processes of the gaseous medium using a pulsed high power laser.[3] A
number of operating parameters may be defined for these types of switches,
which are common to both switching concepts. These parameters can then
form a basis for tailoring specific gases and gas mixtures to optimize
these operating conditions as nearly as possible.

The operating principle of the diffuse switch in the energy-storage
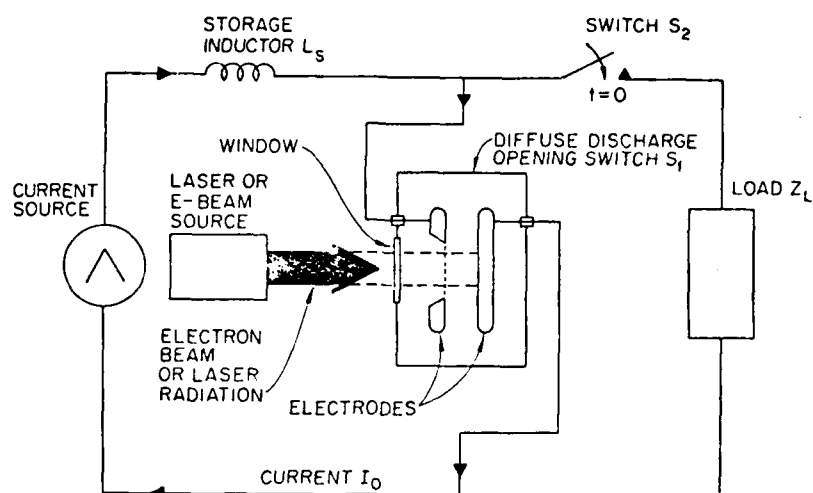cycle is given in Fig. 1 (Ref. 1). In the *conducting* stage, the switch

Fig. 1. Inductive energy discharge circuit (from Ref. 1).

S_2 is open, and the switch S_1 is conducting by means of a diffuse dis-
charge, which is sustained by ionization of the gas mixture using either
an e-beam or a laser. In the opening stage, the external ionization
source is removed, thus opening S_1, and the switch S_2 is closed to
allow the energy stored in the inductor, L_s, to be transferred to the
load, Z_L. It is known, however, that in an inductive system where one
attempts to rapidly open the conducting switch, a very large voltage is
induced across the switch due to the term V_i = -L di/dt (L is the inductance
of L_s in Fig. 1, and i is the current). This induced voltage tends to
maintain a conducting arc between the electrodes of the switch S_1 and to
quote Kristiansen et al.,[1] "How to interrupt the conduction process against
a high driving voltage is the essence of an opening switch."

The circuit equation governing the electron density, n_e, in the
diffuse-discharge switch, S_1, which is driven by an external electron
beam flux J_b at a given E/N, is

$$\frac{dn_e}{dt} = \langle d\sigma/dx \rangle \, J_b W^{-1} - k_a n_e N_a - k_{R_1} n_e n_+ \quad , \tag{1}$$

where $\langle d\varepsilon/dx \rangle$ is the mean energy loss in the direction of the beam, W is the average energy required to produce an ion pair,[4] k_a is the electron attachment rate constant, N_a is the attaching gas number density, k_{R_1} is the two-body recombination coefficient, and n_+ is the positive ion number density. A similar expression may be written when the current in the switch is sustained by resonance (laser) photoionization of the gas mixtures. The current density in the switch J_s is given by Ohm's law, i.e.,

$$J_s = en_e w \quad ,$$ (2)

where w is the electron drift velocity.

In the conducting stage, the electron current density in the switch must be as large as possible for a given e-beam current. In order for the switch to be as effective as possible, the electron loss terms in Eq. (1) must be minimized. Along with the minimization of the electron attachment rate constant k_a, the electron ionization rate constant k_i resulting from the applied electric field must be small,[2] otherwise the switch opening time will be increased considerably. This source of ionization can be ignored provided that $k_i \ll k_a$ during the conducting and opening stages of the switch.

Conversely, the electron gain term $\langle d\varepsilon/dx \rangle \, J_b W^{-1}$ is maximized so as to enhance the current gain in the discharge by minimizing the nonionizing inelastic processes in the gas constitutents, while attempting to maximize their ionization cross sections. To maximize the efficiency of ion pair production, and hence the current in the switch, W must be minimized for a given gas mixture. A further criterion for enhancing the switch current, J_s, from Eq. (2) is to maximize the electron drift velocity (or

mobility) at the given electric field strength during the conduction stage. The desirable characteristics of the gaseous medium during the conduction stage may thus be summarized as follows: (1) maximum electron drift velocity, w; (2) minimum e-beam ionization energy, W; (3) minimum electron loss terms k_a and k_{R_1}; and (4) $k_i \ll k_a$.

In the *opening* stage, the voltage across the switch increases rapidly due to the induced voltage across the inductor, causing an accompanying increase in E/N across the discharge gap. This basic difference between the conducting stage, where the applied conduction voltage is comparatively small ($E/N \simeq 3 \times 10^{-17}$ V cm^2),[3] and the opening stage, where the E/N across the gap may increase to values of $\simeq 120 \times 10^{-17}$ V cm^2, is the key to tailoring gas mixtures with the desired operating characteristics.

In the opening stage, the external electron source is ceased, and the largest rate of decrease in the current of switch S_1 occurs when k_a is as large as possible. Similarly, the response time of the switch is improved from Eq. (2) by choosing a gas mixture in which the electron drift velocity dec ...ses when the E/N across the discharge gap increases. The gas mixture must also be able to withstand a high breakdown field ($\gtrsim 120 \times 10^{-17}$ V cm^2) for successful operation of the switch at very short opening times.

A further desirable characteristic of the gas mixture which becomes important when it is proposed to operate the switch at high repetition frequencies and a closed gas system is that the gas mixture be "self-healing." That is, the composition of the gas mixture is unaffected by the repetitive operation of the switch.[3] This characteristic is unobtainable when using a gas which attaches electrons dissociatively to

form negative ion and neutral fragments. Repetitive operation of the switch will eventually alter the composition of the gas and a possible degradation in *performance* will *result* unless one employs a flowing rather than a closed gas system. It is desirable in these circumstances that electron attachment proceeds via stabilization of the parent negative ion. This attachment mechanism does not lead to ion fragmentation and thus increases the operating life of the gas mixture in the switch.

The desirable characteristics of the gaseous medium during the opening stage may now be summarized:

1. Minimum electron mobility, μ;

2. Maximum electron attachment rate, k_a;

3. High breakdown strength $(E/N_{\ell im} > 120 \times 10^{-17}$ V cm^2);

4. Self-healing gas mixtures for static gas-filled switches.

The desirable characteristics of the gas mixture in terms of the electron drift velocity $w(E/N)$ and $k_a(E/N)$ are shown in Fig. 2. The drift velocity *must be a maximum* at the *E/N* values (indicated by the shaded region characteristic of the conduction stage), and k_a must be as small as possible in this E/N range. In the opening stage, w must be as small as possible and k_a as high as possible at the E/N values (indicated by the shaded region in Fig. 2) characteristic of this stage.

II. TECHNIQUES

We have used experimental techniques that have been developed in this laboratory during the past 10 years to identify gases and gas mixtures which have the desirable characteristics outlined in Section I when used in diffuse discharge-opening switches. These measurements have allowed us to tailor gas mixtures which can optimize the characteristics required in a given switching configuration.

ELECTRON DRIFT/ATTACHMENT CHARACTERISTICS DESIRED IN DIFFUSE-DISCHARGE SWITCHES
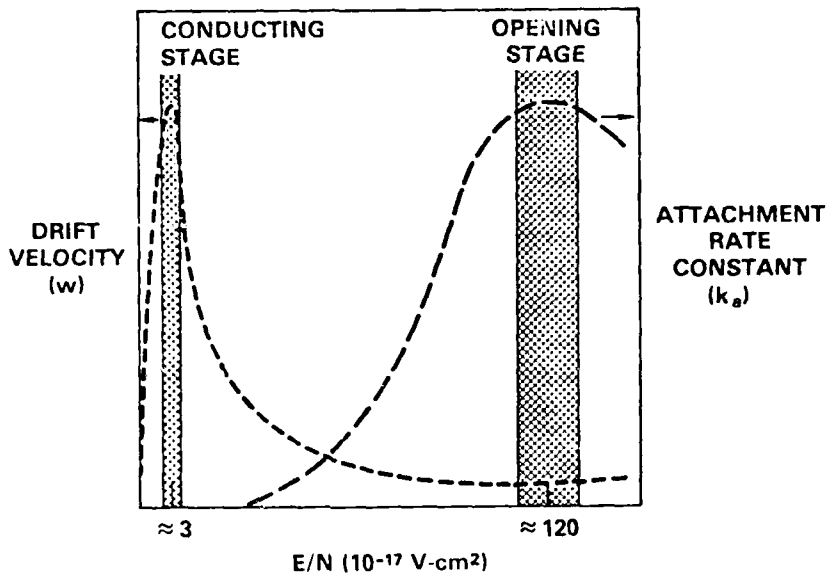
Fig. 2. Schematic illustration of the desirable characteristics of the w(E/N) and k_a(E/N) functions of the gaseous medium in an external'y (e-beam-sustained) diffuse-discharge switch. Indicated in the figure are rough estimates of the E/N values for the conducting and opening stages of the switch.

Measurements of w in pure gases and gas mixtures have been made in the apparatus described by Christophorou et al.[5,6,7] This apparatus has been used to me sure w in gas mixtures for use in high speed proportional counters and to study the density dependence of w in dense polar gases. Electron attachment rate constant, k_a, measurements are obtained as a function of mean electron energy, $\langle\varepsilon\rangle$, in a high pressure electron attachment apparatus which has been described previously.[4,8] This apparatus has been used to screen highly electron attaching gases for

possible use as gaseous dielectrics in high voltage transmission equipment.[9]
These measurements have enabled us to identify several gases with desirable
electron attaching properties[10,11] (Appendix A) for use in diffuse-discharge
opening switches. Electric field breakdown strength measurements are
performed in a *high pressure uniform field breakdown* apparatus described
previously.[12] These measurements enable us to determine the breakdown
strengths of proposed gas mixtures as a function of attaching gas
concentration, thus defining the operating E/N limits of specific gas
mixtures. Negative ion and neutral decomposition fragments produced
under *low energy* electron impact have been studied using a single
collision time-of-flight mass spectrometer apparatus.[13,14] These studies
enable us to identify the fragments produced in the gas discharge and
thus estimate the possible deleterious or beneficial effects that these
fragments will have on the operation of the diffuse-discharge switch.

III. TECHNICAL PROGRESS

The measurements that have been performed during this reporting
period have allowed us to identify several attaching gas/buffer gas
mixtures which have very desirable electron attaching and drift velocity
characteristics for possible use in diffuse-discharge opening switches.
The decomposition products resulting from electron attaching collisions
have been identified, and the operating E/N limits of several gases and
gas mixtures have been determined.

A.   Equipment Modifications and New Experimental Techniques

A new technique for measuring the electron attachment (η/N) and
ionization (α/N) coefficients has been developed using a modification of
the Grünberg[15] method and the "state-of-the-art" data acquisition

capabilities of the Biomation 8100 transient digitizer. Electron attachment and ionization coefficient measurements in several gases and gas mixtures have been obtained over a wide range of E/N and gas pressures using this technique.

A new high-field-uniformity drift assembly has been constructed with a drift gap approximately 3 times that of our present apparatus. A new high-speed (2 ns/channel) Biomation 6500 transient digitizer has been purchased and interfaced with our data acquisition and analysis computer. With these two improvements, we can now accurately measure electron drift velocities in fast gases and gas mixtures up to $\sim5 \times 10^7$ cm/s (i.e., approximately 10 times faster than in the original experiment).

B. Basic Data

We have obtained electron attachment and ionization coefficients in O_2, CF_4, C_2F_6, and C_3F_8 gases using the new method of analysis outlined above. The pressure dependence of the electron attachment coefficient in O_2 and C_3F_8 has also been analyzed. A paper describing this technique and the measurements in these gases is in preparation.

Measurements of α/N and η/N in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures have been obtained over the concentration range of from 0.1 to 30% which can be used in modeling studies of diffuse-discharge switches. These measurements and their significance will be discussed in a paper to be presented at the Third International Swarm Seminar (see Part C of this section).

High-pressure electron attachment rate constant measurements ($k_a = \eta w/N$) have been obtained in N_2 and Ar buffer gases for the per-fluoroalkane series CF_4 to $n-C_6F_{14}$ over the mean electron energy range

from thermal energy ($\sim$0.04 eV) to $\sim$4.8 eV. Knowledge of the electron energy distribution functions for those buffer gases has enabled us to obtain the electron attachment cross sections (σ_a) for these electronegative gases from such measurements. Single collision negative ion production studies have been performed for these gases which have identified the negative ion and neutral fragments which will be produced during the operation of the switching gas discharge.

High-pressure electron attachment rate constant measurements, electron attachment cross sections, and negative ion production as function of electron energy have also been obtained for the ethers $(CF_3)_2O$ and $(CF_3)_2S$. Both $(CF_3)_2O$ and $(CF_3)_2S$ have desirable elec' attaching properties for use in diffuse-discharge switches.

High voltage breakdown strengths ($E/N_{\ell im}$) have been obtained for the gas mixtures C_2F_6/Ar, C_2F_6/CH_4, C_3F_8/Ar, and C_3F_8/CH_4 as a function of the percentage of the electron attaching gas in the buffer gas. These measurements are useful in optimizing the attaching gas concentration and total gas pressure in the operation of practical diffuse-discharge switches.

High-pressure swarm studies are being performed for $CC\ell F_3$ in N_2 and Ar buffer gases as a function of gas temperature over the temperature range 300 to 600 K. Considerable enhancement of the electron attachment rate constant has been observed in this gas over this temperature range.

C. Publications

Preliminary results of the measurements outlined above have been published in the *Proceedings of the Workshop on Gaseous Breakdown Phenomena* sponsored by the Naval Surface Weapons Center in September 1982 (see Appendix B) and in the *Proceedings of the Tamarron (Colorado) Workshop*

on Diffuse Discharge Opening Switches in January 1983. An abstract (Appendix C) has been submitted for a presentation at the IEEE 4th International Pulsed Power Conference in June 1983, and at the Third International Swarm Seminar in August 1983, in which our latest measurements will be reported and discussed. A paper is presently in preparation for journal publication in which our electron attachment and ionization coefficient measurement technique will be outlined, and the measurements in the gases mentioned above will be analyzed.

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APPENDIX A

Gases for possible use in diffuse-discharge switches

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Desirable electron attachment and electron drift characteristics of gases for possible use in diffuse-discharge switches are indicated. Gas mixtures for possible use in externally sustained (e-beam) diffuse-discharge switches are suggested on the basis of electron attachment rate constants and electron drift velocities measured as a function of the density-normalized electric field E/N. Of particular promise are mixtures of Ar and C_3F_8.

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It has been pointed out recently[1,2] that in pulsed-power applications, energy storage using inductive elements could be advantageous because of the high intrinsic energy density: about 10^2 to 10^4 times that for capacitive systems. It appears[1-3] that the main technological problem in inductive storage systems for pulsed-power applications is the need for an opening switch—capable of repetitive operation—to transfer the energy from the storage loop to the load. In this letter we wish to suggest candidate gas mixtures for possible use in externally sustained (e-beam) diffuse-discharge switches.

The requirements of a gaseous medium for use in a diffuse-discharge switch can be understood by realizing that a basic difference between the conducting (storing) and the opening (transferring) stages of the switch (at least in the e-beam-sustained discharge) is the effective value of the density-reduced electric field, E/N (or E/P). In the conducting stage the E/N is low ($\sim 3 \times 10^{-17}$ V cm^2), while in the opening stage the E/N is high ($\sim 120 \times 10^{-17}$ V cm^2). This is most significant and remains a key variable in efforts to tailor gases for optimum performance in both stages. The gas, which in the conducting stage must optimize conduction (high w, no attachment, reduced recombination), in the transferring stage must serve as a high-voltage insulant in order to sustain the high driving voltage and prevent breakdown.

In Fig. 1 we show schematically the desirable characteristics of the gas in terms of the drift velocity $w(E/N)$ and the attachment rate constant $k_a(E/N)$. The drift velocity w must be a maximum at the E/N values (indicated by the shaded region in Fig. 1) characteristic of the conducting stage, and k_a must be as small as possible in this E/N range. In the opening state (Fig. 1), w must be as small as possible and k_a as high as possible at the E/N values (indicated by the shaded region in Fig. 1) characteristic of this stage.

Fast gases having the general characteristics of $w(E/N)$ shown in Fig. 1 have been reported by us[1] (e.g., Ar + CF$_4$ mixtures) which are free of electron attachment at low E/N. Promising mixtures that are comprised of Ar and CF$_4$ are shown in Fig. 2. The mixture composition and E/N can be chosen such as to maximize w in the conducting stage. It is also seen that at high E/N, the w of such mixtures falls off

considerably, a property desirable in the opening stage of the switch[5] (see Fig. 1).

To become effective for the opening stage of the switch, such gases must, in addition, have a high dielectric strength. To achieve this, the mixture must effectively remove electrons by electron attachment forming negative ions.[6,7] Since in the opening stage of the switch E/N is very high, the gas must be capable of removing electrons with energies in excess of thermal energy. It thus seems that a fast gas mixture (i.e., one with high w) such as Ar + CF$_4$ must be mixed with a third gas which does not attach thermal and near-thermal energy electrons but which attaches electrons at higher energies (say, from ~ 0.5 to 2 eV). Candidates for such electron attaching gases to mix with the fast mixtures of Ar + CF$_4$ are shown in Fig. 3.

Special attention is drawn to the gas (CF$_3$)$_2$S which is seen (Fig. 3) to capture electrons rather strongly above thermal energies and which in SF_6 is an excellent gas dielectric having (de univ) in field breakdown strength 1.5 times that of SF$_6$ (Ref. 9). A mass spectrometric study of (CF$_3$)$_2$S has shown[10] that the dominant anion is CF$_3$S$^-$ whose yield peaks at ~ 0.65 eV, a finding consistent with the k_a vs $\langle \epsilon \rangle$
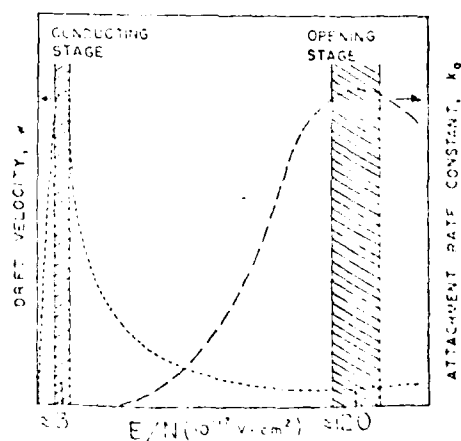

FIG. 1. Schematic illustration of the desirable characteristics of the $w(E/N)$ and $k_a(E/N)$ functions of the gaseous medium in an externally (e-beam-sustained) diffuse-discharge switch. Indicated in the figure are rough estimates of the E/N values for the conducting and the opening stage of the switch.

[a] Also, Department of Physics, The University of Tennessee, Knoxville, Tennessee 37916.
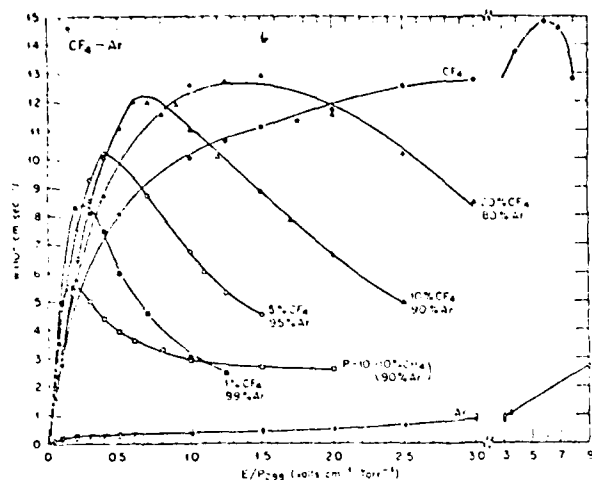
FIG. 2. w vs E/P_{298} for Ar and Ar/CF$_4$ mixtures (from Ref. 4).

FIG. 4. w vs E/N for Ar and Ar/C$_3$F$_8$ mixtures.

data in Fig. 3. The vapor pressure of (CF$_3$)$_2$S at ~ 20 °C is ~ 4.4 atm.

It follows from the above discussion that ternary mixtures comprised of Ar + CF$_4$ and (CF$_3$)$_2$S (or another electron attaching additive with the appropriate properties, Figs. 1 and 3) are good candidates for diffuse-discharge switches. It is, however, preferable to have a binary rather than a ternary mixture and to identify, for example, a gas which would serve the role of both CF$_4$ and (CF$_3$)$_2$S when mixed with Ar. In the search for such a gas we focused on C$_3$F$_8$. The attachment rate constant k_a as a function of $\langle \epsilon \rangle$ for C$_3$F$_8$ is shown in Fig. 3. Although the k_a for C$_3$F$_8$ is lower in magnitude than that for (CF$_3$)$_2$S, it has a very desirable $\langle \epsilon \rangle$

dependence (i.e., it is very small at low $\langle \epsilon \rangle$ and large at high $\langle \epsilon \rangle$). Mass spectrometric studies in a single collision experiment have shown[11] that the dominant anion is F^- with a peak at 2.9 eV. Swarm studies at atmospheric gas pressures indicate[12] that the predominant electron attachment process in this gas proceeds via stabilization of the parent negative ion. This attaching gas is thus "self-healing" in that it does not fragment considerably in an electron attaching collision and may be useful in a closed-cycle switch as well.

In Fig. 4 are presented w vs E/N for Ar and Ar/C$_3$F$_8$ mixtures. Due to apparatus limitations, we were unable to obtain data for higher percentages of C$_3$F$_8$ in Ar (our apparatus is being modified to allow such measurements). However, based on the data on Ar + CF$_4$ (Fig. 2) and similar data on Ar + C$_2$F$_6$ (not presented because of space limitation) we can infer that mixtures comprised of 10–20% C$_3$F$_8$ and 90–80% Ar will have maximum values of w in excess of 10^7 cm s^{-1} and $w(E/N)$ functions maximizing in the E/N range of 2–4×10^{-17} V cm^2, which is roughly the range characteristic of the conductive stage of the switch.
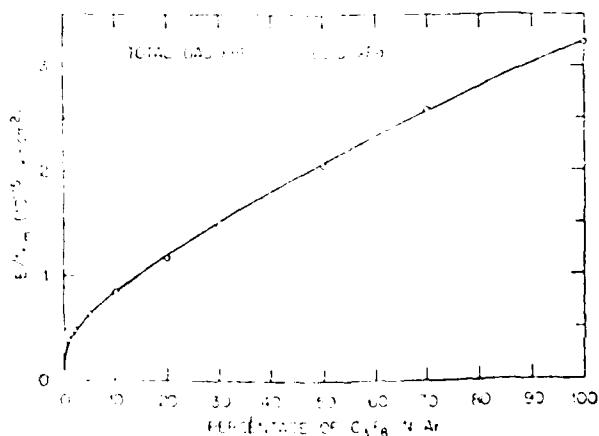
We have conducted dc uniform field breakdown

FIG. 3. Electron attachment rate constant k_a as a function of mean electron energy $\langle \epsilon \rangle$ for (CF$_3$)$_2$S and C$_3$F$_8$ (present work) and 1,2-C$_2$Cl$_3$F$_3$, 1,1,2-C$_2$Cl$_3$H$_3$, and 1,1-C$_2$Cl$_2$H$_4$ from Ref. 8. The relative breakdown strengths V_s'' shown in the figure are from Ref. 7 except those for (CF$_3$)$_2$S, which are from Ref. 9.

FIG. 5. $(E/N)_{\lim}$ vs percentage of C$_3$F$_8$ in Ar under dc uniform field conditions.

strength measurements on Ar/C_3F_8 mixtures and determined (Fig. 5) the limiting value, $(E/N)_{lim}$, of E/N (i.e., the E/N value at which breakdown occurs) as a function of the percentage of C_3F_8 in Ar. It can be seen from the data in Fig. 5 that for Ar/C_3F_8 mixtures containing ~15–20% C_3F_8, the $(E/N)_{lim}$ is $\gtrsim 120 \times 10^{-17}$ V cm^2, i.e., such mixtures can withstand the voltage levels characteristic of the opening stage of the switch.

Although further work is necessary, on the basis of the preliminary data presented, it can be suggested that mixtures comprised of ~15–20% C_3F_8 and 80–85% Ar may possess both of the required characteristics (see Fig. 1) of a switching gas and can thus be suggested as good candidates for diffuse-discharge switches.[13]

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[13] The vapor pressure of C_3F_8 at ~20 °C is ~7.8 atm; C_3F_8 is listed in [*Matheson Gas Data Book*, 5th ed., edited by W. Braker and A. L. Mossman (New Jersey, 1971), p. 467] as nontoxic, nonflammable, unreactive, and thermally stable; its dc uniform field breakdown voltage is 0.9 that of SF_6.

APPENDIX B
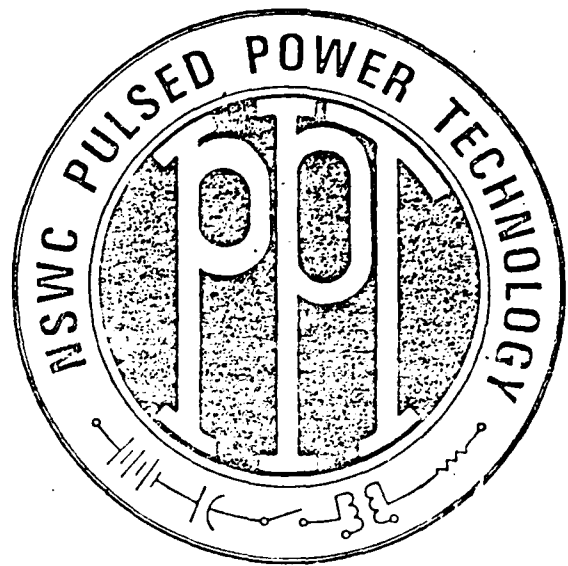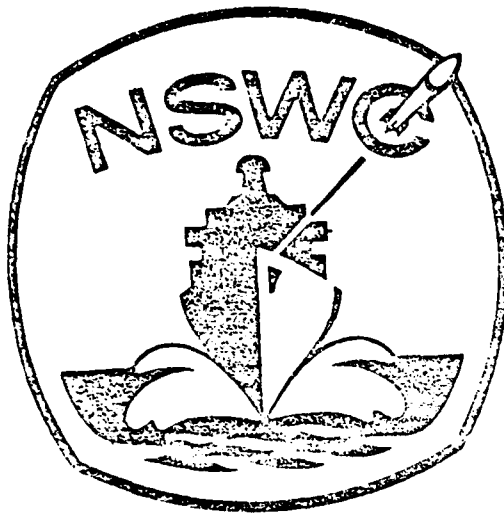
WORKSHOP ON GASEOUS BREAKDOWN PHENOMENA

15 SEPTEMBER 1982

NAVAL SURFACE WEAPONS CENTER

Gases for possible use in diffuse-discharge switches

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Desirable electron attachment and electron drift characteristics of gases for possible use in diffuse-discharge switches are indicated. Gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches are suggested on the basis of electron attachment rate constants and electron drift velocities measured as a function of the density-normalized electric field E/N. Of particular promise are mixtures of Ar and C_3F_8.

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It has been pointed out recently[1,2] that in pulsed-power applications, energy storage using inductive elements could be advantageous because of the high intrinsic energy density: about 10^2 to 10^4 times that for capacitive systems. It appears[1-3] that the main technological problem in inductive storage systems for pulsed-power applications is the need for an opening switch—capable of repetitive operation—to transfer the energy from the storage loop to the load. In this letter we wish to suggest candidate gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches.

The requirements of a gaseous medium for use in a diffuse-discharge switch can be understood by realizing that a basic difference between the conducting (storing) and the opening (transferring) stages of the switch (at least in the *e*-beam-sustained discharge) is the effective value of the density-reduced electric field, E/N (or E/P). In the conducting stage the E/N is low ($\sim 3 \times 10^{-17}$ V cm^2), while in the opening stage the E/N is high ($\sim 120 \times 10^{-17}$ V cm^2). This is most significant and remains a key variable in efforts to tailor gases for optimum performance in both stages. The gas, which in the conducting stage must optimize conduction (high w, no attachment, reduced recombination), in the transferring stage must serve as a high-voltage insulant in order to sustain the high driving voltage and prevent breakdown.

In Fig. 1 we show schematically the desirable characteristics of the gas in terms of the drift velocity $w(E/N)$ and the attachment rate constant $k_a(E/N)$. The drift velocity w must be a maximum at the E/N values (indicated by the shaded region in Fig. 1) characteristic of the conducting stage, and k_a must be as small as possible in this E/N range. In the opening state (Fig. 1), w must be as small as possible and k_a as high as possible at the E/N values (indicated by the shaded region in Fig. 1) characteristic of this stage.

Fast gases having the general characteristics of $w(E/N)$ shown in Fig. 1 have been reported by us[4] (e.g., Ar + CF$_4$ mixtures) which are free of electron attachment at low E/N. Promising mixtures that are comprised of Ar and CF$_4$ are shown in Fig. 2. The mixture composition and E/N can be chosen such as to maximize w in the conducting stage. It is also seen that at high E/N, the w of such mixtures falls off

considerably, a property desirable in the opening stage of the switch[5] (see Fig. 1).

To become effective for the opening stage of the switch, such gases must, in addition, have a high dielectric strength. To achieve this, the mixture must effectively remove electrons by electron attachment forming negative ions.[6,7] Since in the opening stage of the switch E/N is very high, the gas must be capable of removing electrons with energies in excess of thermal energy. It thus seems that a fast gas mixture (i.e., one with high w) such as Ar + CF$_4$ must be mixed with a third gas which does not attach thermal and near-thermal energy electrons but which attaches electrons at higher energies (say, from ~ 0.5 to 2 eV). Candidates for such electron attaching gases to mix with the fast mixtures of Ar + CF$_4$ are shown in Fig. 3.

Special attention is drawn to the gas (CF$_3$)$_2$S which is seen (Fig. 3) to capture electrons rather strongly above thermal energies and which itself is an excellent gas dielectric having a dc uniform field breakdown strength 1.2 times that of SF$_6$ (Ref. 9). A mass spectrometric study of (CF$_3$)$_2$S has shown[10] that the dominant anion is CF$_3$S$^-$ whose yield peaks at ~ 0.65 eV, a finding consistent with the k_a vs (ϵ)
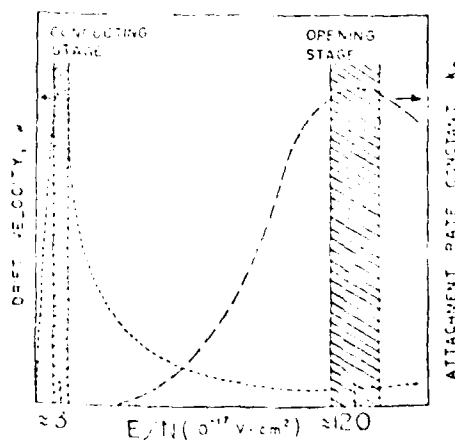

FIG. 1 Schematic illustration of the desirable characteristics of the $w(E/N)$ and $k_a(E/N)$ functions of the gaseous medium in an externally (*e*-beam-sustained) diffuse-discharge switch. Indicated in the figure are rough estimates of the E/N values for the conducting and the opening stage of the switch.

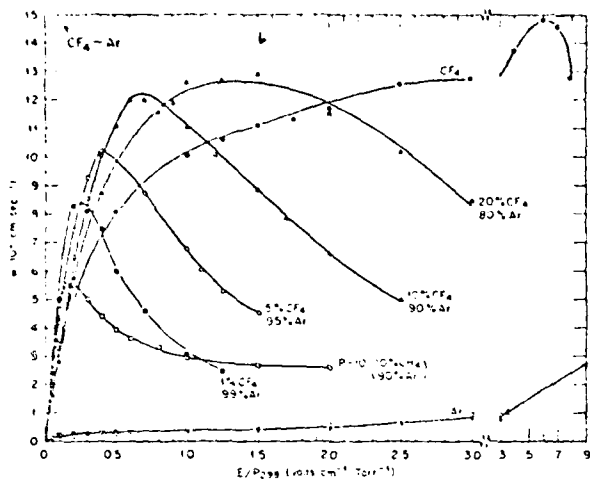[a] Also, Department of Physics, The University of Tennessee, Knoxville, Tennessee 37916

FIG. 2. w vs E/P_{298} for Ar and Ar/CF$_4$ mixtures (from Ref. 4).

FIG. 4. w vs E/N for Ar and Ar/C$_3$F$_8$ mixtures.

lata in Fig. 3. The vapor pressure of (CF$_3$)$_2$S at ~20 °C is ~4.4 atm.

It follows from the above discussion that ternary mixtures comprised of Ar + CF$_4$ and (CF$_3$)$_2$S (or another electron attaching additive with the appropriate properties, Figs. 1 and 3) are good candidates for diffuse-discharge switches. It is, however, preferable to have a binary rather than a ternary mixture and to identify, for example, a gas which would serve the role of both CF$_4$ and (CF$_3$)$_2$S when mixed with Ar. In the search for such a gas we focused on C$_3$F$_8$. The attachment rate constant k_a as a function of $\langle\epsilon\rangle$ or C$_3$F$_8$ is shown in Fig. 3. Although the k_a for C$_3$F$_8$ is lower in magnitude than that for (CF$_3$)$_2$S, it has a very desirable $\langle\epsilon\rangle$

dependence (i.e., it is very small at low $\langle\epsilon\rangle$ and large at high $\langle\epsilon\rangle$). Mass spectrometric studies in a single collision experiment have shown[11] that the dominant anion is F^- with a peak at 2.9 eV. Swarm studies at atmospheric gas pressures indicate[12] that the predominant electron attachment process in this gas proceeds via stabilization of the parent negative ion. This attaching gas is thus "self-healing" in that it does not fragment considerably in an electron attaching collision and may be useful in a closed-cycle switch as well.

In Fig. 4 are presented w vs E/N for Ar and Ar/C$_3$F$_8$ mixtures. Due to apparatus limitations, we were unable to obtain data for higher percentages of C$_3$F$_8$ in Ar (our apparatus is being modified to allow such measurements). However, based on the data on Ar + CF$_4$ (Fig. 2) and similar data on Ar + C$_2$F$_6$ (not presented because of space limitation) we can infer that mixtures comprised of 10–20% C$_3$F$_8$ and 90–80% Ar will have maximum values of w in excess of 10^7 cm s^{-1} and $w(E/N)$ functions maximizing in the E/N range of 2–4×10^{-17} V cm^2, which is roughly the range characteristic of the conductive stage of the switch.

We have conducted dc uniform field breakdown

FIG. 3. Electron attachment rate constant k_a as a function of mean electron energy $\langle\epsilon\rangle$ for (CF$_3$)$_2$S and C$_3$F$_8$ (present work) and 1,2-C$_2$Cl$_2$F$_4$, 1,1,2-C$_2$Cl$_3$H$_3$, and 1,1-C$_2$Cl$_2$H$_4$ (from Ref. 8). The relative breakdown strengths V_s^R shown in the figure are from Ref. 7 except those for (CF$_3$)$_2$S, which are from Ref. 9.
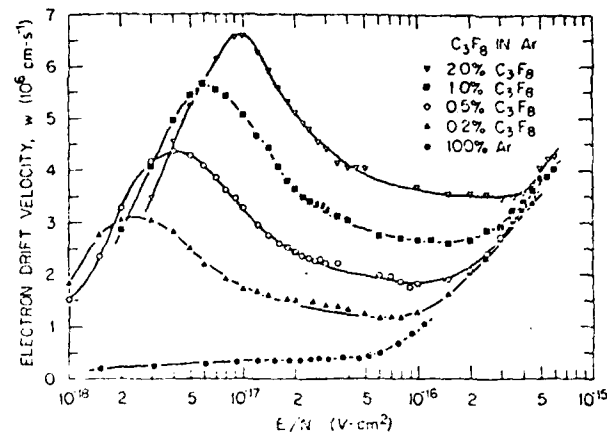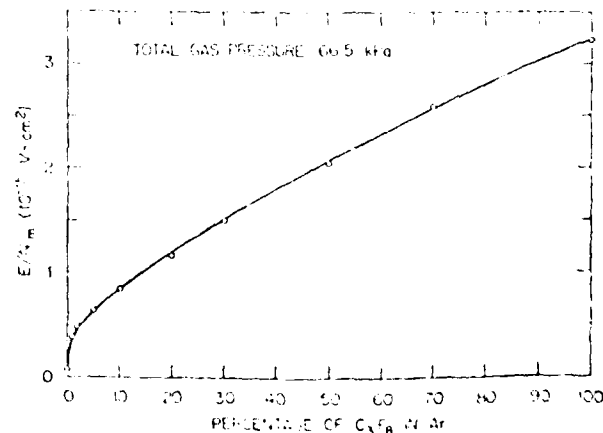

FIG. 5. $(E/N)_{\lim}$ vs percentage of C$_3$F$_8$ in Ar under dc uniform field conditions.

strength measurements on Ar/C_1F_8 mixtures and determined (Fig. 5) the limiting value, $(E/N)_{lim}$, of E/N (i.e., the E/N value at which breakdown occurs) as a function of the percentage of C_1F_8 in Ar. It can be seen from the data in Fig. 5 that for Ar/C_1F_8 mixtures containing $\sim 15-20\%$ C_1F_8, the $(E/N)_{lim}$ is $\gtrsim 120 \times 10^{-17}$ V cm^2, i.e., such mixtures can withstand the voltage levels characteristic of the opening stage of the switch.

Although further work is necessary, on the basis of the preliminary data presented, it can be suggested that mixtures comprised of $\sim 15-20\%$ C_1F_8 and 80-85% Ar may possess both of the required characteristics (see Fig. 1) of a switching gas and can thus be suggested as good candidates for diffuse-discharge switches.[13]

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[9] L. G. Christophorou, D. R. James, R. Y. Pai, R. A. Mathis, I. Sauers, D. H. Smith, L. C. Frees, M. O. Pace, D. W. Bouldin, C. C. Chan, A. Fatheddin, and S. R. Hunter, Oak Ridge National Laboratory Report ORNL/TM-7624 (1981).

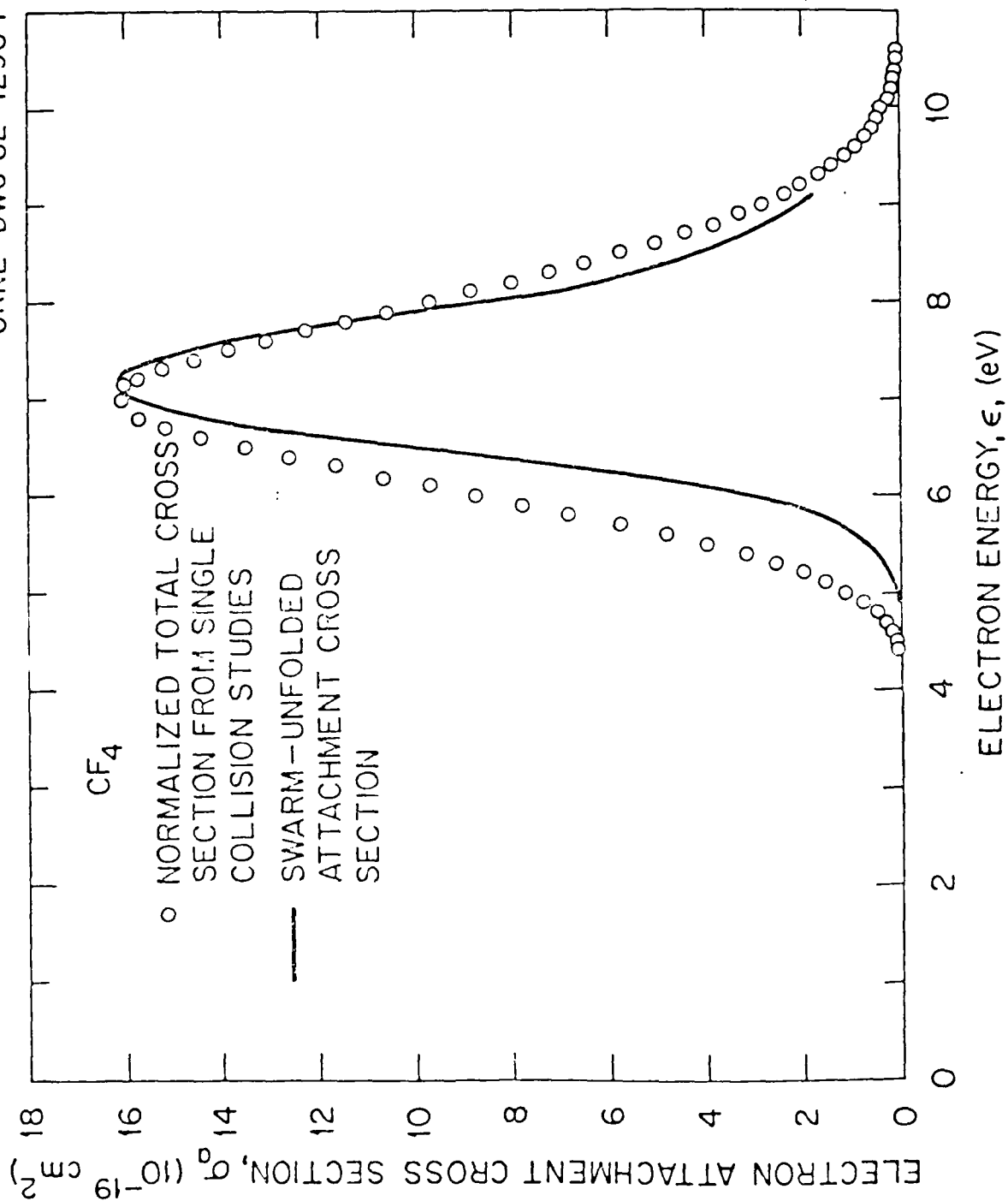[10] S. M. Spyrou (private communication 1981).

[11] L. G. Christophorou, D. R. James, R. Y. Pai, R. A. Mathis, I. Sauers, D. H. Smith, L. C. Frees, S. R. Hunter, M. O. Pace, D. W. Bouldin, S. M. Spyrou, and A. Fatheddin, Oak Ridge National Laboratory Report ORNL/TM-7862, 1981, p. 14.

[12] S. R. Hunter, L. G. Christophorou, D. R. James, and R. A. Mathis, in *Gaseous Dielectrics III*, edited by L. G. Christophorou (Pergamon, to be published).
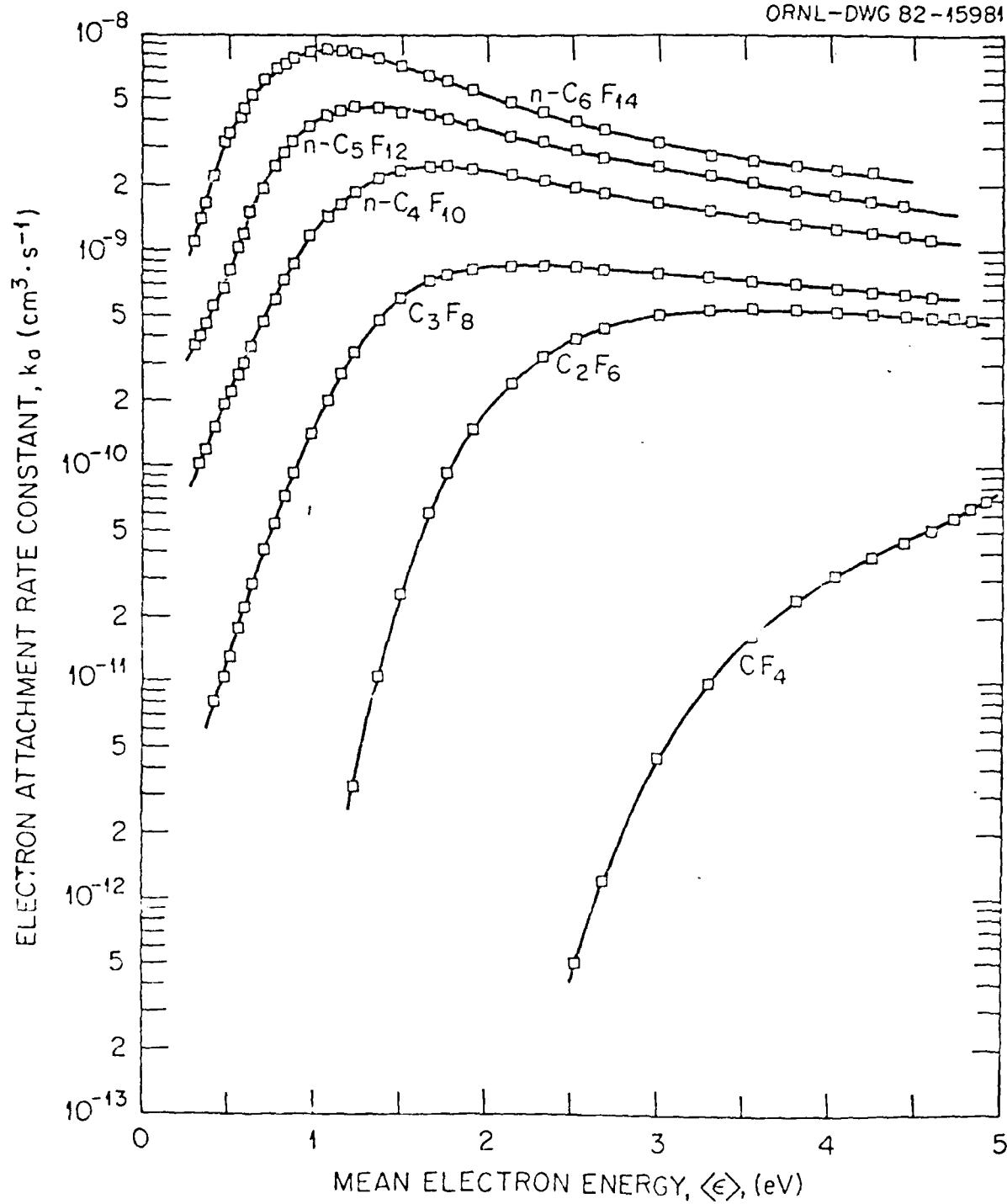
[13] The vapor pressure of C_1F_8 at ~ 20 °C is ~ 7.8 atm; C_1F_8 is listed in [*Matheson Gas Data Book*, 5th ed., edited by W. Braker and A. L. Mossman (New Jersey, 1971), p. 467] as nontoxic, nonflammable, unreactive, and thermally stable; its dc uniform field breakdown voltage is 0.9 that of SF_6.

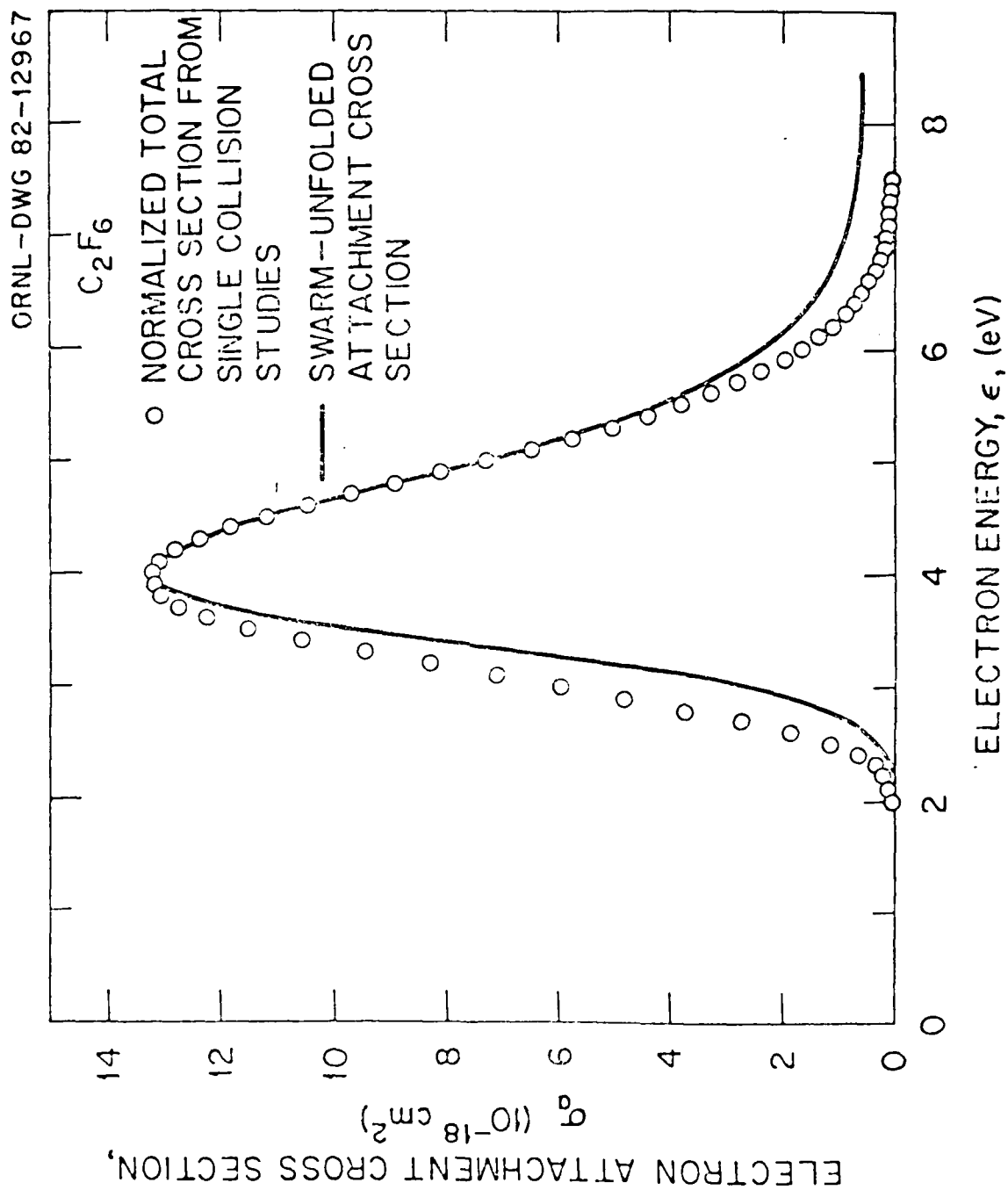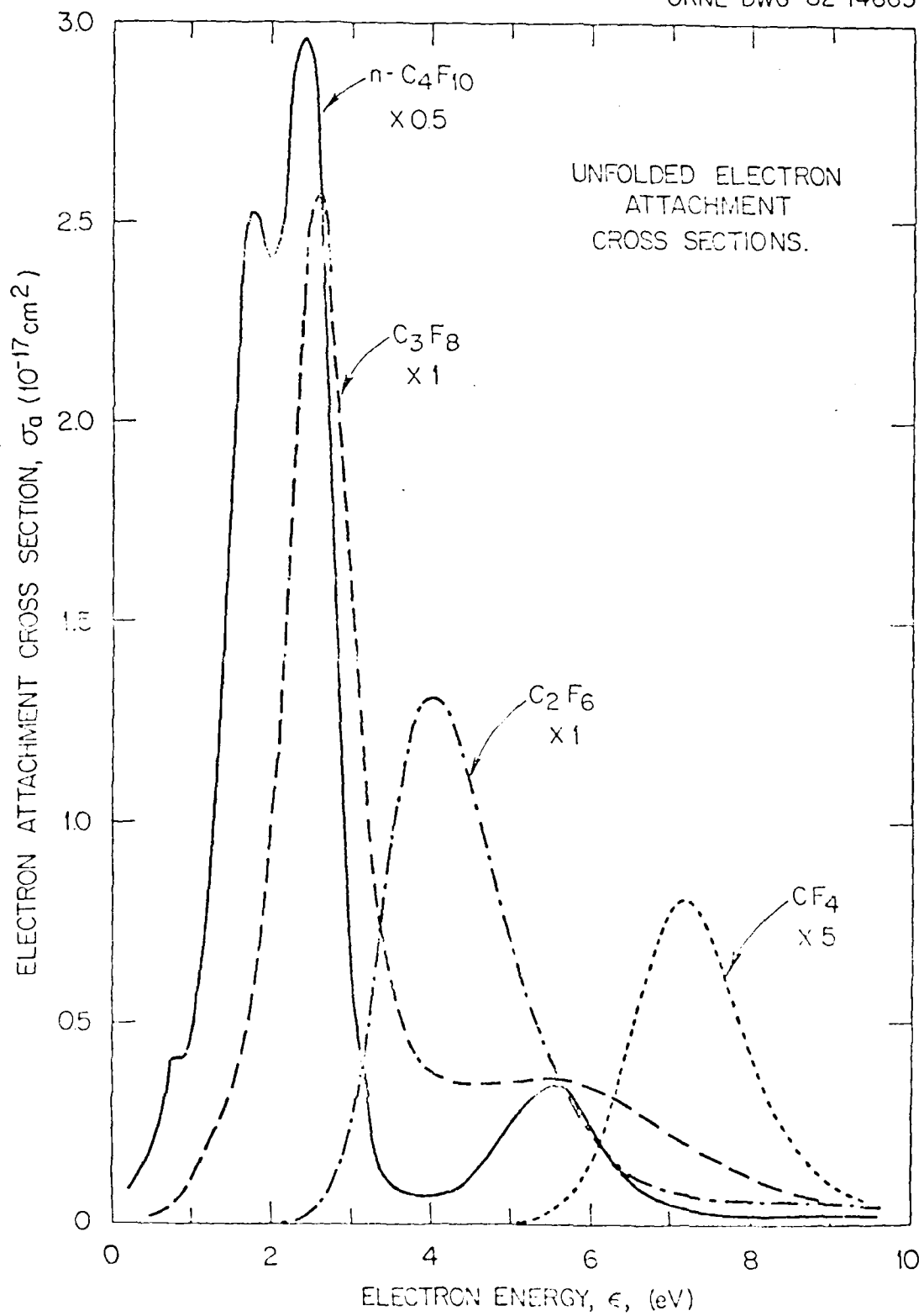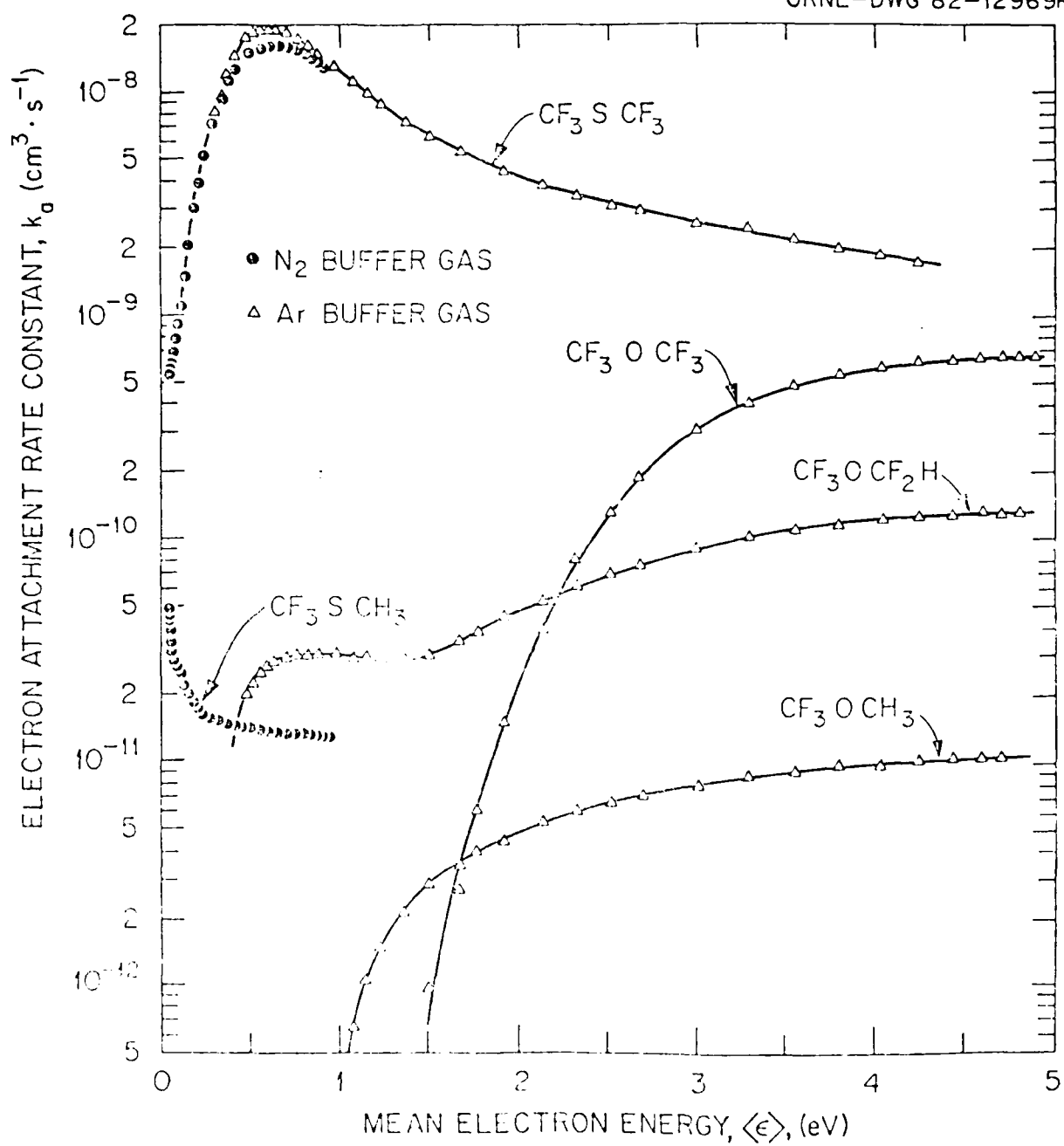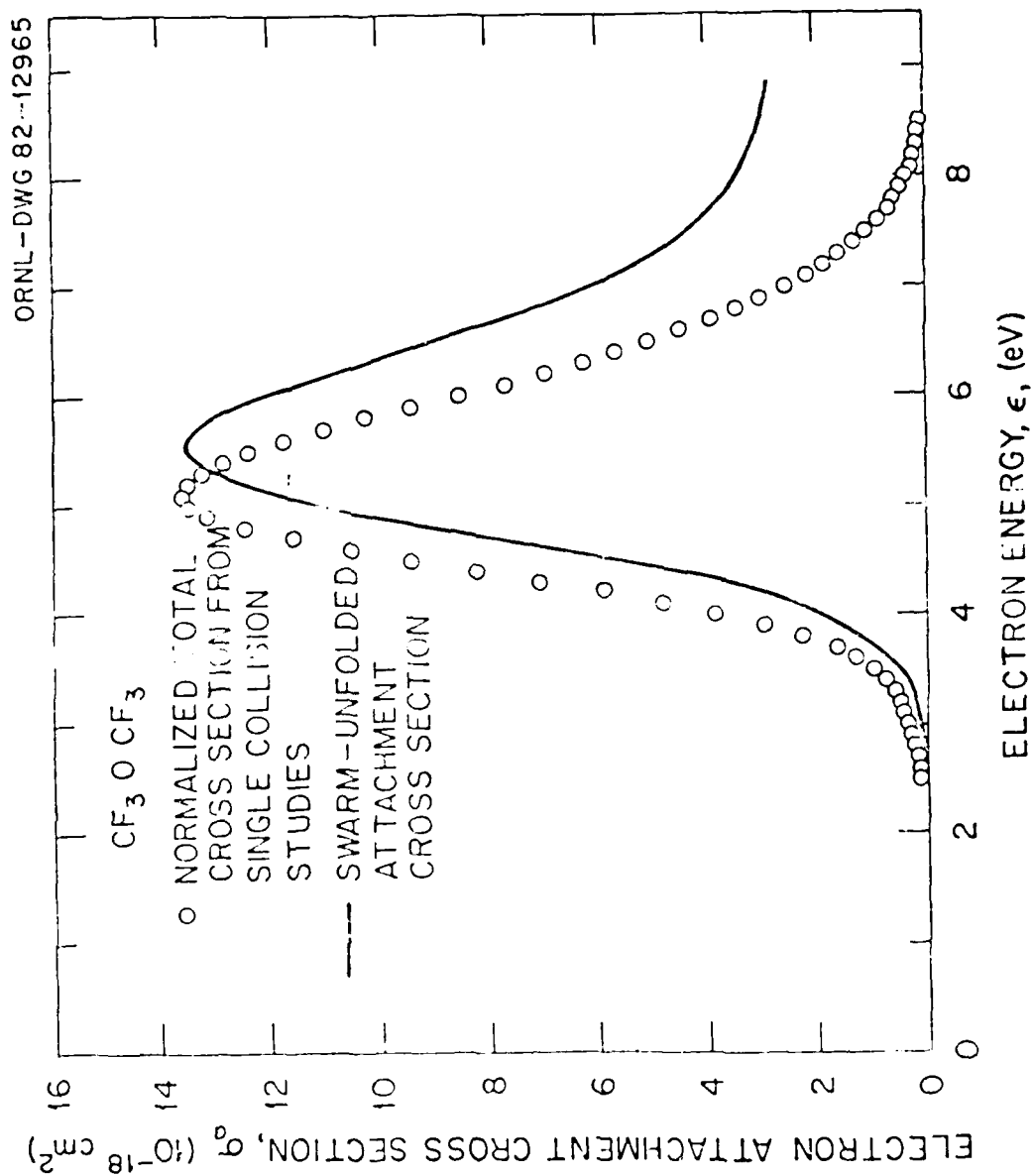ORNL–DWG 82–12964

CF_4

o NORMALIZED TOTAL CROSS SECTION FROM SINGLE COLLISION STUDIES

— SWARM–UNFOLDED ATTACHMENT CROSS SECTION

ELECTRON ENERGY, ϵ, (eV)

ELECTRON ATTACHMENT CROSS SECTION, q_a (10^{-19} cm^2)

ORNL-DWG 82-15981

ORNL-DWG 82-12967

C_2F_6

o NORMALIZED TOTAL
  CROSS SECTION FROM
  SINGLE COLLISION
  STUDIES

— SWARM-UNFOLDED
  ATTACHMENT CROSS
  SECTION

ELECTRON ENERGY, ϵ, (eV)

ELECTRON ATTACHMENT CROSS SECTION, q_a (10^{-18} cm^2)

ORNL-DWG 82-14663

UNFOLDED ELECTRON
ATTACHMENT
CROSS SECTIONS.

ORNL—DWG 82—12969R

ORNL—DWG 82—12965

CF₃ O CF₃

○ NORMALIZED TOTAL
CROSS SECTION FROM
SINGLE COLLISION
STUDIES

— SWARM—UNFOLDED
ATTACHMENT
CROSS SECTION

ELECTRON ENERGY, ε, (eV)

ELECTRON ATTACHMENT CROSS SECTION, σ_a (10^{-18} cm²)
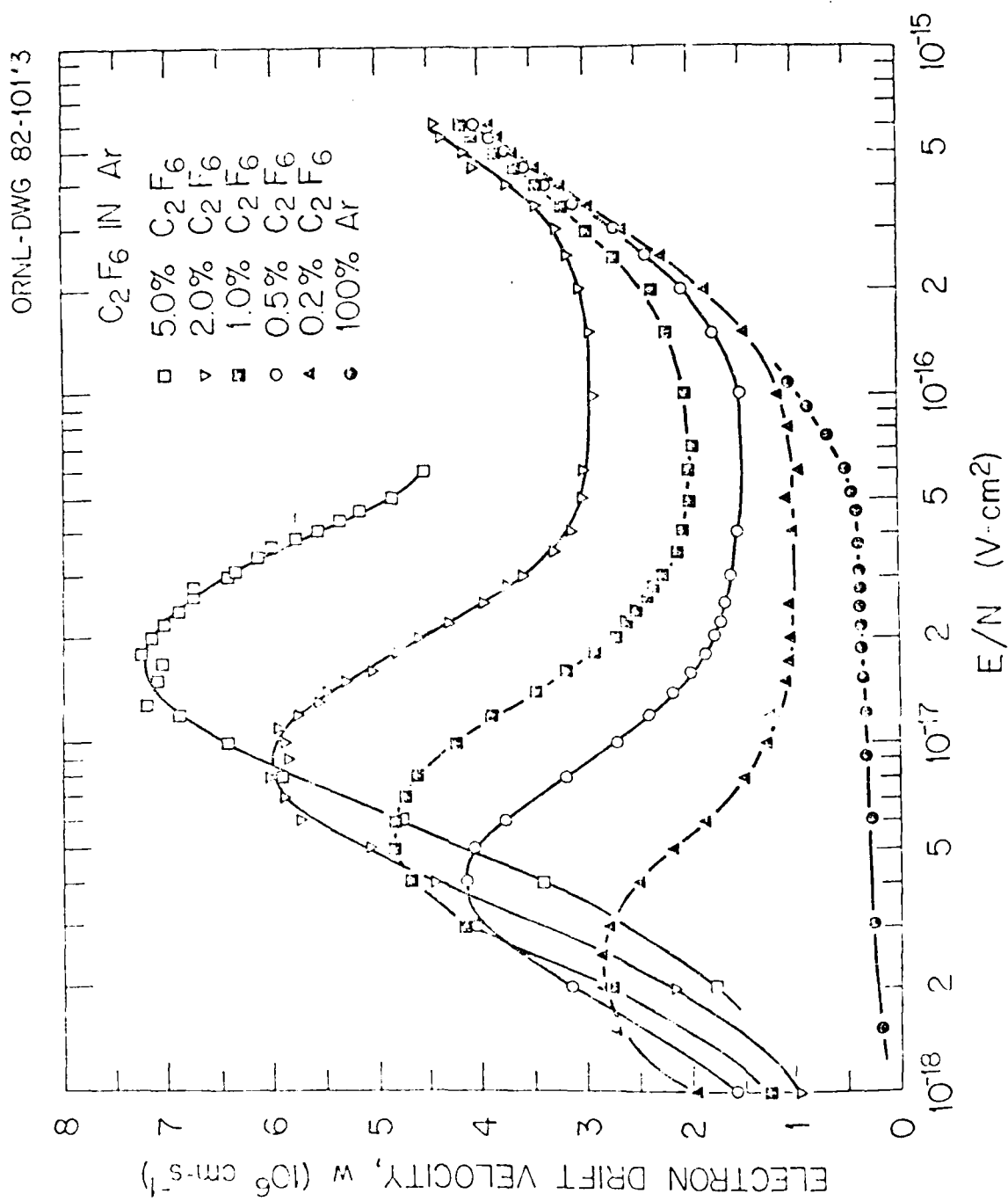
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APPENDIX C

BASIC STUDIES OF GASES FOR DIFFUSE-DISCHARGE SWITCHING APPLICATIONS[*]

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The basic processes which underlie the successful tailoring of gases/ mixtures with high dielectric strengths and appropriate conduction characteristics for diffuse-discharge switching applications will be discussed. Recent results on electron attachment rate constants and cross sections as well as on the fragmentation by electron impact of CF_4, C_2F_6, C_3F_8, CF_3CCF_3, and CF_3CCF_3 which are of potential interest in diffuse-discharge technologies will be presented. Recent findings on the electron attachment, electron drift velocity, and breakdown properties of a number of mixtures comprised of electron attaching and electron drift-velocity-enhancing components (e.g., CF_3CCF_3/Ar, C_3F_8/Ar, C_2F_6/Ar, C_2F_6/CH_4) will be reported. The observed increase in the electron attachment rate constant of $CClF_3$ with temperature over a *wide mean energy range* (~0.5 to 4.0 eV) and its implications for diffuse-discharge switching applications will be reported also.